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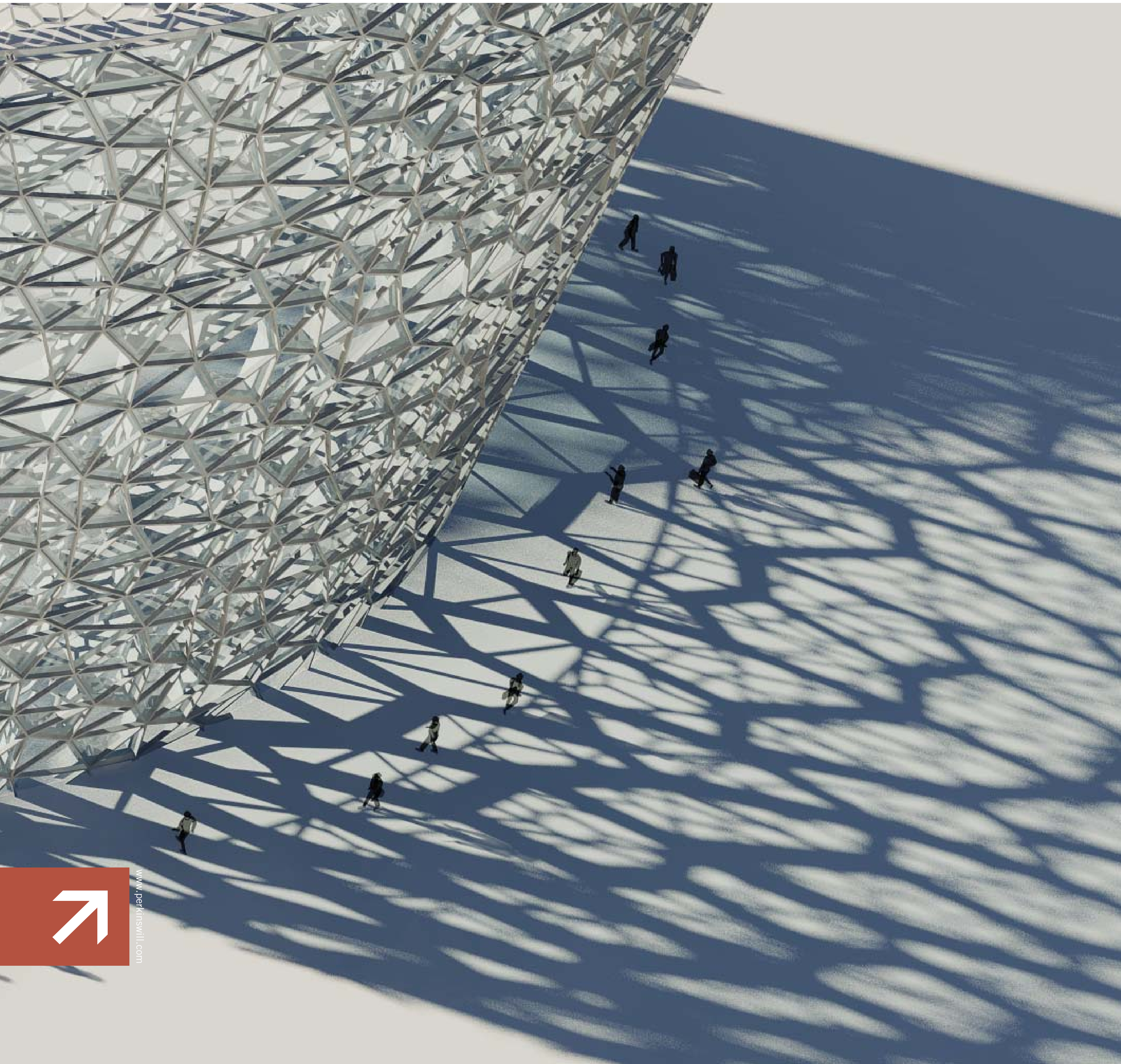
Research Journal

2010 / VOL 02.01



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04.
COMPARATIVE ANALYSIS OF FLOORING MATERIALS:
Environmental and Economic Performance

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ABSTRACT
The environmental impact of flooring materials is the aggregate of impacts of raw material properties and composition across all stages of the product life cycle including extraction, manufacturing, packaging and transportation, use and disposal. In this analysis, linoleum, vinyl composition tile (VCT), nylon carpet tile, composite marble tile, ceramic tile, terrazzo, cork and rubber flooring are compared. Life cycle assessment is performed for these selected materials, where both environmental and economic factors are examined. It is important to understand performance of various materials when design factors are changed. Therefore, this analysis compares environmental impact when design requirements are varied and material characteristics are constant.

Past research is presented, where relative results generally agree among several studies. However, various methodologies have been utilized for lifecycle assessment with differing measurements for environmental performance, thus comparative analysis is not permissible. Economic factors have not been reported in previous studies, therefore, the primary objective of this study is to investigate environmental and economic performance of various flooring materials.

Building for Environmental and Economic Sustainability (BEES) software is utilized to measure combinatory performance of the selected materials for raw material acquisition, manufacturing process, transportation, installation, use, recycling and waste management. Three scenarios are investigated, where initially equal weights are given to both environmental and economic factors. Second case is primarily associated with economic and third with the environmental performance. Results indicate that cork, linoleum and rubber flooring materials should be considered when environmental factors are the primary concern and when both environmental and economic factors are equally weighted.

KEYWORDS: life cycle analysis, environmental performance, flooring materials

1.0 INTRODUCTION
Material selection is a crucial component of sustainable design and sustainable selection, where specification decisions are based upon numerous factors. Among a few are material properties, production, cost and effects on indoor air quality. Prioritizing materials based on their environmental impact is becoming a common practice, with the objective to minimize negative environmental impacts. However, measuring environmental impact for various building materials is relatively challenging, since complex factors and relationships must be taken into account[1].

This study compares flooring materials based on environmental and economic costs to understand benefits and drawbacks of choosing certain products. Literature review presents several past studies and their results. Although general conclusions of these studies are comparable, it should be noted that yielded results vary depending on the input information and analysis methodology. In order to understand environmental performance of several flooring materials in relation to economic factors, life cycle assessment (LCA) is conducted for linoleum, vinyl composition tile, nylon carpet tile, composite marble tile, ceramic tile, terrazzo, cork and rubber flooring.

2.0 RESEARCH CONTEXT AND PAST STUDIES

Different approaches in assessing environmental impact respond to different questions and interpretation of results must take into account analysis methodologies. Relationships between different methodologies can be:

- Consecutive, where results of one approach become input data for another approach
- Complementary, where two approaches use the same basis for comparison, but yield different results since different dimensions are investigated
- Competing, where two approaches use the same method for comparison and investigate the same dimensions, but yield different results since different assumptions are made during the analysis
- Encompassing, where a certain approach is an integral part of another
- Overlapping, where both approaches yield same results since the methodology is identical.

LCA considers cradle-to-grave impacts, where material contents, production, energy requirements, and waste are analyzed to produce a total environmental impact. ISO 14040-14043 standards specify the methodology that should be followed, where inventory data are associated with specific environmental impact categories such as depletion of abiotic resources, global warming, ozone layer depletion, human toxicity, water toxicity, acidification, nutrification and photochemical oxidant creation[2, 3, 4]. Inventory analysis is typically utilized to compare productive cycle, material preparation, raw materials, manufacturing, packaging, transportation, use and disposal for a functional unit of a material. Building for Environmental and Economic Sustainability (BEES) software measures the environmental performance of building products using the ISO 14040 series of standards and ASTM E917-05e1 standard for measuring economic performance[5]. Detailed description of the model components is presented later in this article.

Several previous studies have investigated environmental impact of flooring materials and are briefly reviewed. Potting and Block investigated environmental performance of linoleum, vinyl, wool carpet and nylon carpet[6]. Impacts that were analyzed include depletion of raw materials, energy requirement for production, global warming, acidification, ozone creation, ozone depletion, eutrophication, waste production and effects on human health. Functional area of 10.76 square feet (1m^2) was studied with set lifetime of 15 years for all four types of materials. Environmental profiles and results of this study are shown in Table 1. Conclusions indicated that linoleum is the most environmentally favorable material and that vinyl is the least. Differentiation between different types of carpet flooring based on environmental performance is more difficult and conclusion about preferred carpet flooring was not drawn. Authors indicated that maintenance and cost analysis were not performed and that further analysis is desirable.

Table 1: Environmental profile per functional area of different flooring materials (Source Potting and Block, 1995).

Impact	Linoleum	Vinyl	Wool carpet	Nylon carpet
Cumulative energy requirement (MJ)				
Feedstock requirement	—	97	48	154
Process energy	40	103	109	175
Global warming (g of CO2 equivalents)	2600	9500	64300	13500
Eutraphication (g of phosphate equivalents)	60	2	1550	14
Acidification (g of SOx equivalents)	10	170	170	80
Ozone creation (g of ethylene equivalents)	4	18	44	17
Waste (g)				
Hazardous waste	400	600	600	650
Non-hazardous waste	1500	2000	3400	2800

Table 2: Environmental rating for flooring materials (Source: Altshuler et al., 2007).

Impact catergory	Sheet vinyl	VCT	Linoleum	Cork
Acidification	1	5	6	10
Eutrophication	4	8	1	10
Smog	1	5	4	10
Ozone depletion	1	5	6	7
Global climate change	1	3	6	10
Fossil fuel depletion	2	7	1	9
Ecotoxicity	1	6	4	10

Table 3: Ratings for health effects associated with flooring materials (Source: Altshuler et al., 2007).

Impact catergory	Material	Impact category	Material
Cancer	1. Sheet vinyl 2. VCT 3. Linoleum 4. Cork	Total human health	1. VCT 2. Sheet vinyl 3. Linoleum 4. Cork

Petersen and Solberg conducted an analysis for greenhouse gas emissions and associated costs of wood flooring, linoleum, vinyl, wool carpet and nylon carpet[7]. The focus of the study was to analyze wood products and competing materials and their effect on global warming, particularly emission of greenhouse gases (CO_2, CH_4 and N_2O). Analyzed functional area was 10.76 square feet ($1m^2$). Emission rates were reported in relation to avoided tons of greenhouse gases per cubic meter of flooring and the results are 0.1-1.9 for linoleum, 0.2-2.3 for vinyl, 0.9-2.5 for nylon carpet and 11.8-15.5 for wool carpet. Authors noted that further research is necessary to link life cycle assessment with economic modeling.

US Green Building Council conducted an investigation into the environmental and health impacts of PVC materials for buildings. Two types of PVC-based materials for flooring were analyzed (sheet vinyl and vinyl composition tile), and two alternative non-PVC materials (linoleum and cork)[8]. Lifecycle assessment and risk assessment were performed, where LCA was based on Environmental Protection Agency's TRACI method[9]. Impact categories included several environmental aspects such as acidification, ecotoxicity, eutrophication, fossil fuel depletion; combined environmental and health effects such as ozone layer depletion and smog; and health effects. EPA TRACI method relies on normalized measures of impact categories and their risks to the environment and human health, where severity of the risk is represented by a numeric value. Based on this method, lower values indicate that a certain material poses higher risks. Results of this study are shown in Tables 2 and 3.

All of the referenced past studies agree in relative rankings of environmental performance of different flooring materials. However, economic aspects have not been reported. In order to compare economic impacts, the following section focuses on the combination of environmental and economic factors.

3.0 ENVIRONMENTAL AND ECONOMIC PERFORMANCE

3.1 Methods of Measurement

Combined environmental and economic performance analysis of different flooring materials is necessary in order to compare benefits and adverse effects. Building for Environmental and Economic Sustainability 4.0 (BEES) software, developed by the National Institute of

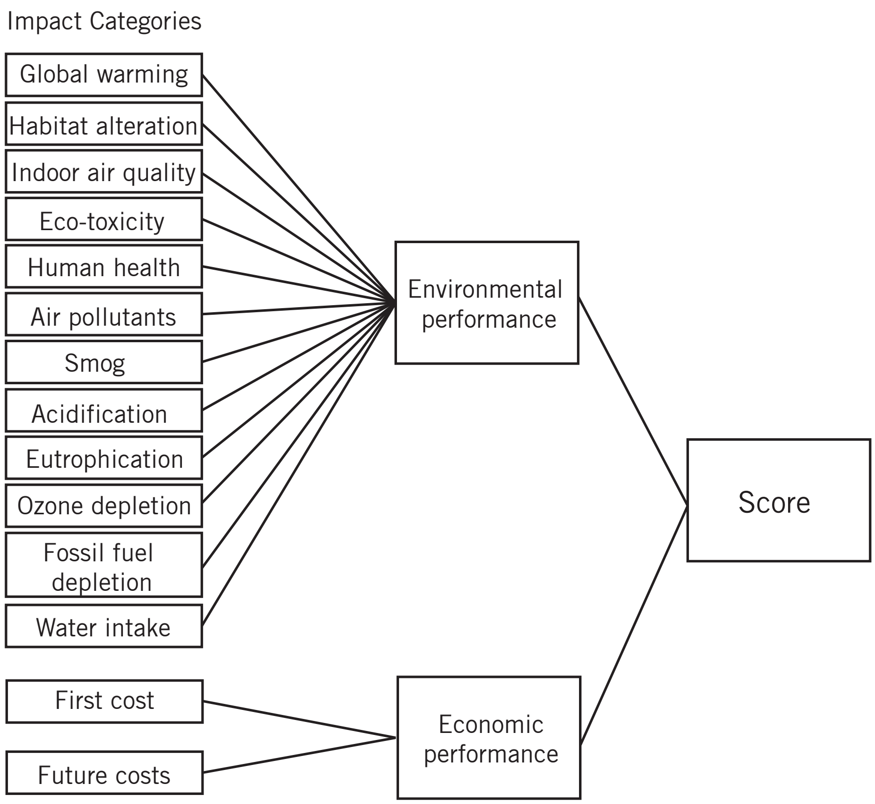


Figure 1: BEES method for measuring environmental and economic impacts.

Standards and Technology, has been utilized for comparative analysis presented in this article[10, 11]. BEES measures environmental performance of building materials and products based on ISO 14040 series of standards and includes all stages of the product's life (raw material acquisition, manufacturing, transportation, installation, use, recycling and waste management). Economic performance is measured using the ASTM E917-05e1 standard for indicating economic impacts over product's life-cycle[5]. Environmental and economic performances are combined to assign an overall impact measure using the ASTM standard for Multiattribute Decision Analysis.

Figure 1 indicates how these two performance indicators are weighted to assign scores for different materials. Environmental performance is measured across all life cycle stages for twelve categories (global warming, habitat alteration, indoor air quality, eco-toxicity, human health, air pollutants, smog, acidification, eutrophication, ozone depletion, fossil fuel depletion and water intake). Economic performance considers initial costs,

Table 4: Relative importance weights for environmental impact categories.

Impact catergory	Relative importance weight (%)
Global warming	16
Habitat alteration	16
Indoor air quality	11
Eco-toxicity	11
Human health	11
Air pollutants	6
Smog	6
Acidification	5
Eutrophication	5
Ozone depletion	5
Fossil fuel depletion	5
Water intake	3

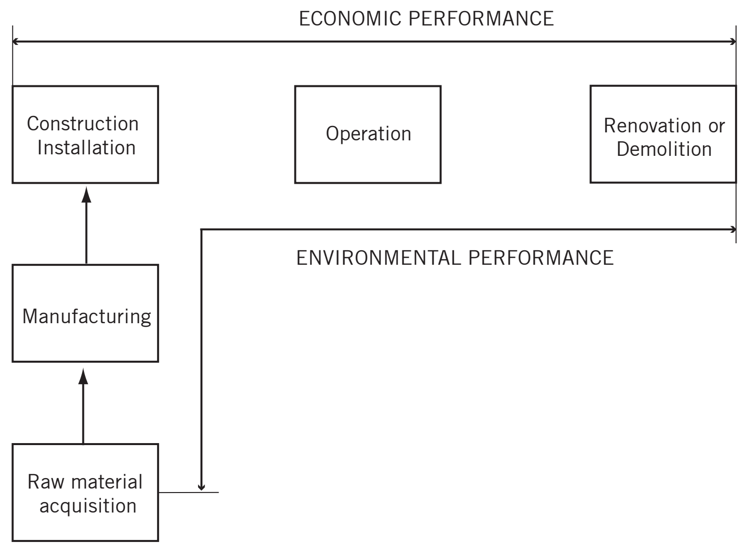


Figure 2: Product life cycle in relation to economic and environmental performance.

operation, maintenance, repair and disposal. Impact categories and relative importance are following Environmental Protection Agency's recommendations[11,12]. Table 4 shows relative importance weights for environmental categories, which are used to determine the overall score of individual materials in conjunction with economic performance.

In the BEES model, economic performance is measured over a 50-year study period. This same period is used to evaluate all products, even if they have different useful lives. Product replacements are accounted for materials that have shorter lives and end-of-life inventory flows are prorated for products with longer lives. Figure 2 indicates how environmental and economic performance is measured. Environmental impact is computed for the entire life-cycle of a product, while economic performance for purchasing, operation and life cycle of the material within the 50-year period.

3.2 Limitations of the Model

The overall performance scores do not represent absolute performance, but rather proportional or relative performance among alternatives. Also, two types of products are included in the database—generic and specific products for which manufacturing data is available. Product composition, manufacturing methods, fuel mixes, transportation practices, useful lives and costs can vary from generic to individual products and therefore, generic product group may not represent the performance of a specific product if the material composition is radically different. The analysis discussed in this article considers generic products.

3.3 Comparison of Flooring Materials

Eight different flooring materials are investigated:

- Vinyl composition tile (VCT)
- Linoleum
- Nylon carpet tile
- Ceramic tile
- Composite marble tile
- Terrazzo
- Cork
- Rubber

Data for VCT, linoleum, nylon carpet tile, ceramic tile, composite marble tile, terrazzo and cork was obtained from BEES software, while data for rubber flooring was obtained from Gunther and Langowski[13], Wilke et al.[14], Tagisaki and Ito[15], Chau et al.[16] and calculated per functional unit to correspond to respective impact categories. BEES does not contain data for rubber flooring, thus these sources were used to compute impact values for functional unit of the material.

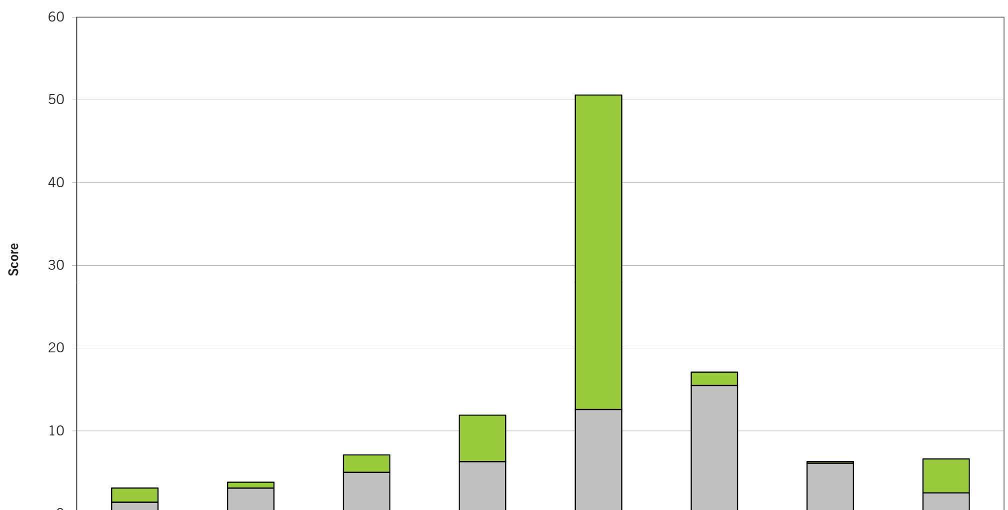
Lifetime expectancy and durability of the flooring material varies according to the type, but are normalized in this analysis as explained in the previous section. Typically, carpets are used for about ten years, although the technical lifetime can be up to fifteen years[17]. VCT lifetime is around thirty years, but it depends on the location and wear. Linoleum lifetime is typically thirty to forty years. Ceramic tile lifetime is fifty years and terrazzo and composite marble tile is up to seventy-five years[18]. In terms of maintenance, VCT requires stripping and surface recoating. Linoleum only requires wet or dry cleaning. Energy requirements for vacuuming carpet flooring and cork flooring can be considerable. Ceramic tile, terrazzo and composite marble tile also require cleaning and occasional sealing.

Three different scenarios are investigated, where the initial scenario considers equal distribution between environmental and economic factors. Second scenario favors economic factors with 90 percent of weight. The last scenario favors environmental factors, where 90% of weight assigned to environmental impacts.

Equal distribution presents a design scenario where environmentally conscious design considerations are balanced by economic factors. Smaller normalized scores indicate improved performance among alternatives. Results show that although VCT would be the most economical choice of material, cork and linoleum flooring have much better environmental performance followed by rubber flooring and nylon carpet tile. Figure 3 shows overall performance scores for economic and environmental effects with equal distribution.

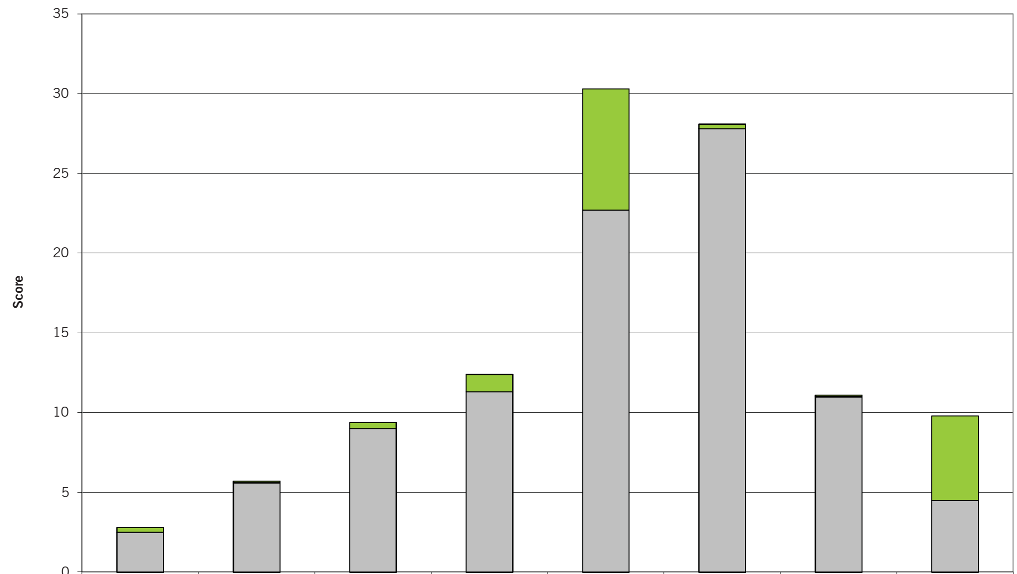
Figure 4 indicates scores when primarily economic considerations are taken into account. Figure 5 shows results when environmental performance is the driving factor.

Based on these scenarios, it is evident that different requirements can impact the overall relative score. When economic and environmental considerations are weighted equally, VCT, linoleum flooring, cork and rubber flooring are comparable based on the overall score. When environmental performance is the driving factor, cork, linoleum, rubber flooring and terrazzo are comparable.



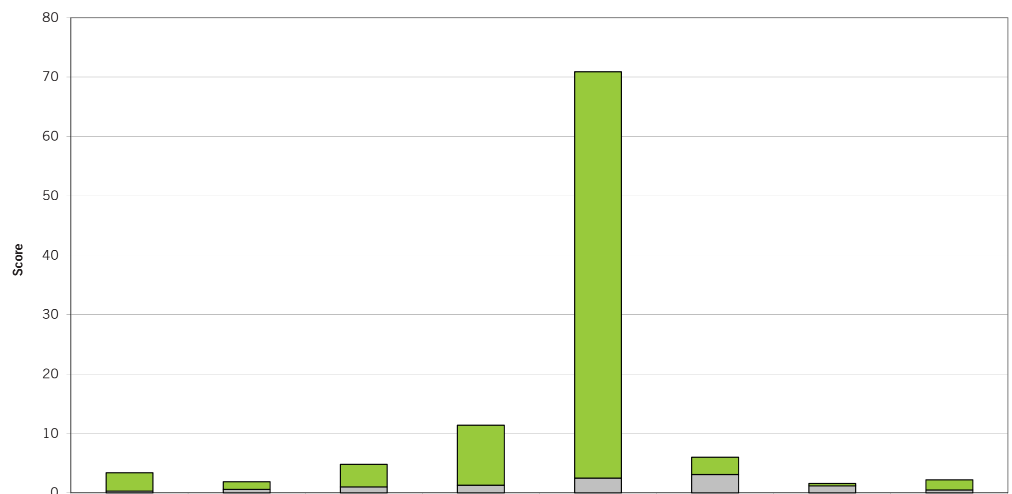
	VCT	Linoleum	Nylon carpet tile	Ceramic tile	Marble tile	Terrazzo	Cork	Rubber
Environmental Performance 50%	1.7	0.7	2.1	5.6	38	1.6	0.2	4.1
Economic Performance 50%	1.4	3.1	5	6.3	12.6	15.5	6.1	2.5

Figure 3: Overall normalized performance score of different flooring materials with equal economic and environmental performance.



	VCT	Linoleum	Nylon carpet tile	Ceramic tile	Marble tile	Terrazzo	Cork	Rubber
Environmental Performance 10%	0.3	0.1	0.4	1.1	7.6	0.3	0.1	5.3
Economic Performance 90%	2.5	5.6	9	11.3	22.7	27.8	11	4.5

Figure 4: Overall performance score of different flooring materials when economic performance is the primary design requirement..



	VCT	Linoleum	Nylon carpet tile	Ceramic tile	Marble tile	Terrazzo	Cork	Rubber
Environmental Performance 90%	3.1	1.3	3.8	10.1	68.4	2.9	0.4	1.7
Economic Performance 10%	0.3	0.6	1	1.3	2.5	3.1	1.2	0.5

Figure 5: Overall performance score of different flooring materials when environmental performance is the primary design requirement.

3.4 Environmental Impact Categories Data

Data for selected environmental impact categories is reviewed in order to indicate values that were used to derive environmental performance scores presented in the previous section. Since the overall environmental performance score is derived by assigning relative weights to each impact category, this section presents actual numeric values that represent specific impacts for each material type. Data is presented for global warming impact, indoor air quality, acidification and fossil fuel depletion.

Figure 6 presents global warming impact for the selected flooring materials. Cork, linoleum and rubber flooring have smaller impact than VCT. Ceramic tile, nylon carpet tile, terrazzo and composite marble tile have similar global warming impact, where majority of carbon dioxide emissions are associated with raw material acquisition and the manufacturing process.

Figure 7 indicates indoor air quality impact, where terrazzo and cork have insignificant values and linoleum, rubber flooring and nylon carpet tile have low amount of total volatile organic compounds (TVOCs). Ceramic tile and composite marble tile have higher content of TVOCs and VCT has the highest content, which is mainly associated with the operation phase.

Figure 8 shows acidification impact, where cork and linoleum flooring are the most favorable. Composite marble tile, ceramic tile and terrazzo have moderate values, while rubber flooring and nylon carpet tile have significant impacts. Impact values are highest for raw material acquisition and the manufacturing process and less for transportation.

Fossil fuel depletion impact is presented in Figure 9, where cork, rubber flooring and linoleum have smaller values than VCT. Ceramic tile, nylon carpet tile, terrazzo and composite marble tile have high impact rates, where values are primarily associated with raw materials acquisition, manufacturing and transportation.

Embodied energy indicates the amount of energy required to extract, process, transport, install and dispose or recycle a material. Figure 10 indicates embodied energy associated with selected flooring materials, where renewable and nonrenewable fractions are expressed per functional unit.

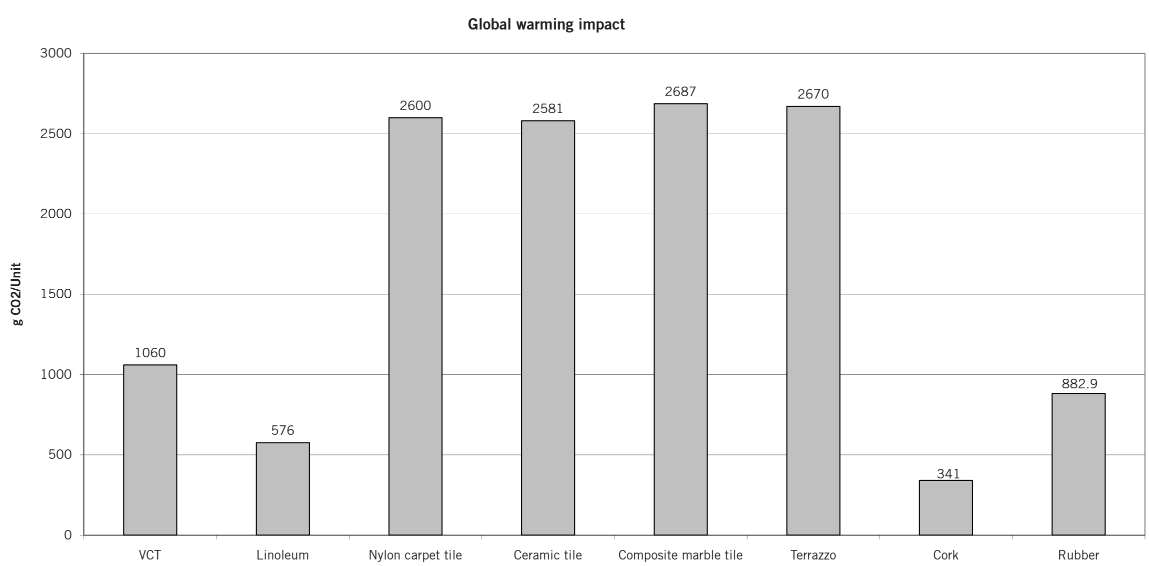


Figure 6: Global warming impact for selected flooring materials.

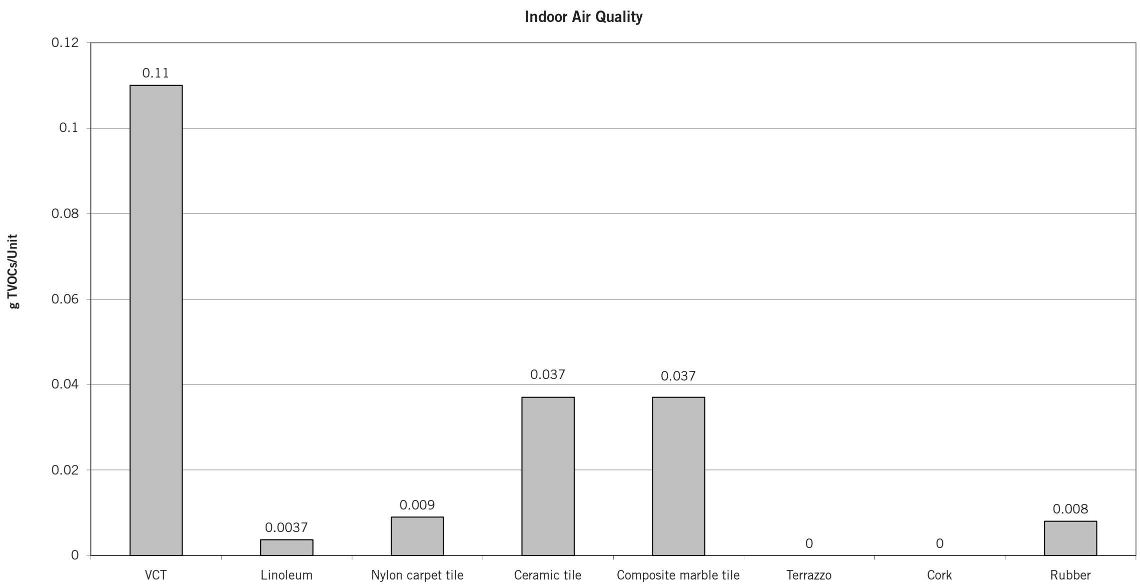


Figure 7: Indoor air quality impact.

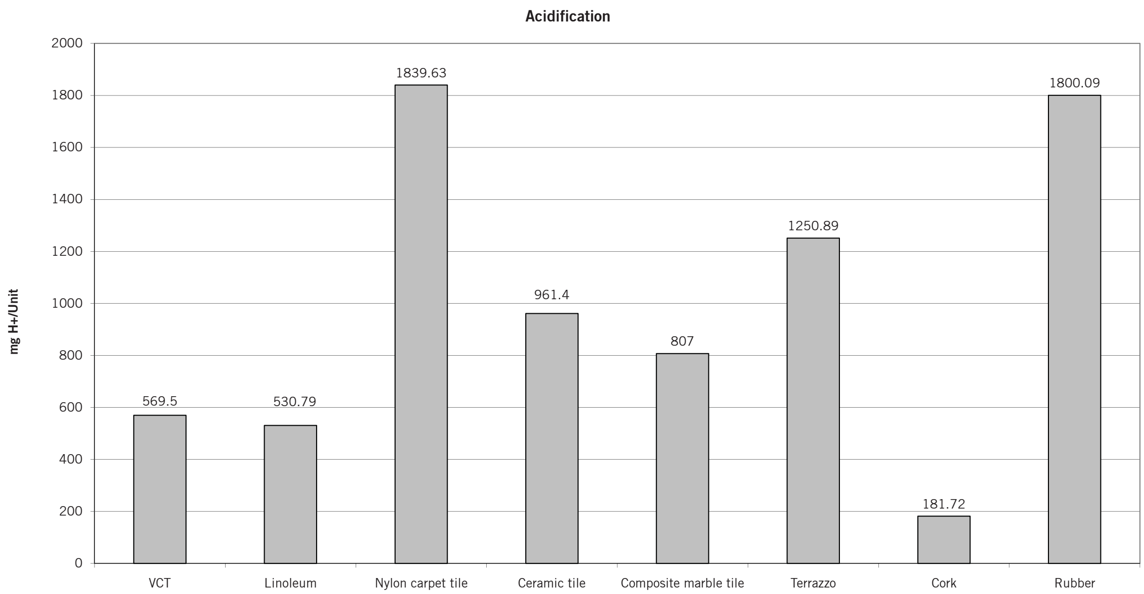


Figure 8: Acidification impact for selected flooring materials.

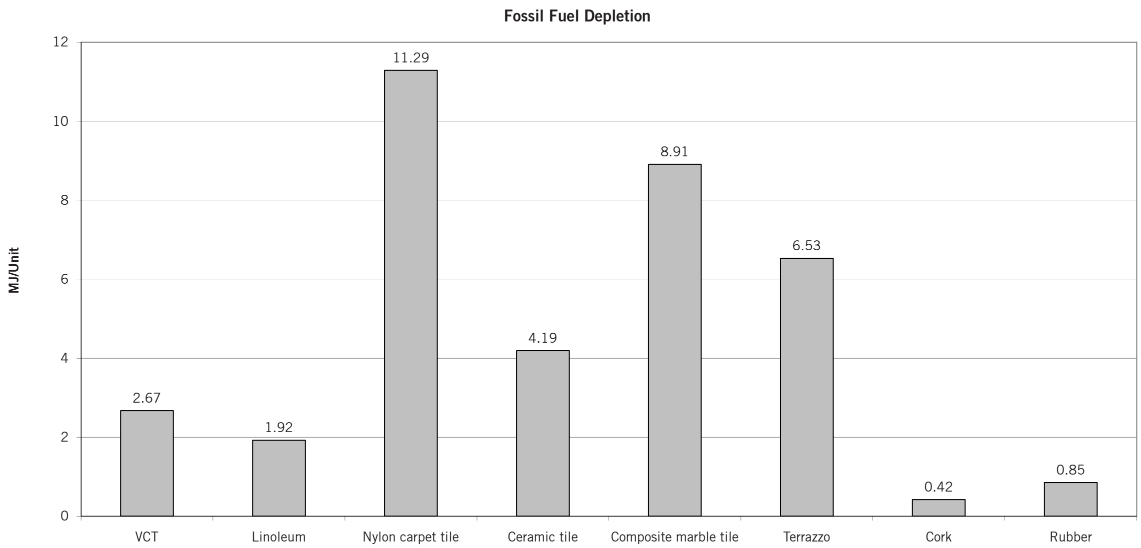


Figure 9: Fossil fuel depletion impact.

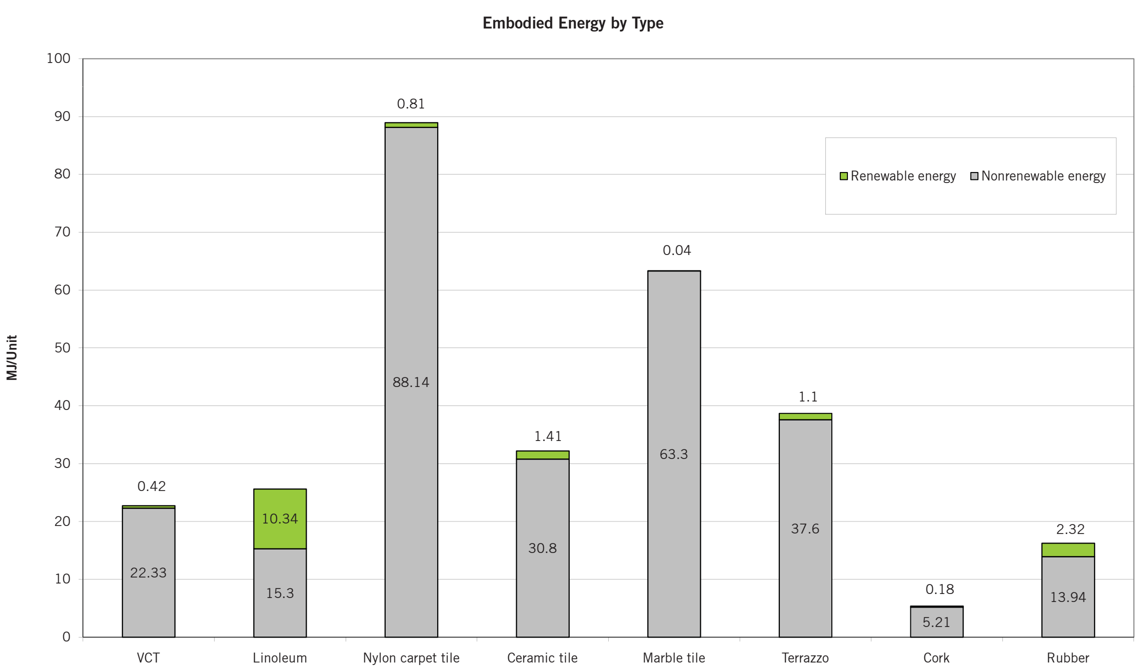


Figure 10: Embodied energy for flooring materials.

4.0 CONCLUSION

It is evident that there is not a single flooring material that has the best environmental performance across all selection criteria. Selection of flooring materials should be based on overall environmental impact, expected life-time of the material, considerations for maintenance and repair as well as performance for the particular functional application. Results of the life cycle assessment indicate that cork, linoleum and rubber flooring materials perform better than VCT for the majority of environmental impact categories. Hence, in scenarios balancing economics and environment, these flooring materials perform relatively similarly. Although VCT is the least expensive choice, environmental performance should be taken into account as well as its impact on indoor air quality. Nylon carpet tile has moderate environmental performance and higher costs over the life cycle. Terrazzo has relatively good environmental performance, but life cycle costs are high. Ceramic and composite marble tile have poor environmental performance, which is mainly associated with raw material acquisition and manufacturing process.

Results of the comparative analysis presented in this article agree with previous studies. However, they also illustrate economic performance aspects that have not been previously reported. It is evident that cork, linoleum and rubber flooring materials should be selected when environmental factors are the primary concern and when both environmental and economic factors are equally weighted. Higher life cycle cost of other material types (nylon carpet tile, terrazzo, ceramic and composite marble tile) and environmental performance should be taken into account when selecting appropriate flooring materials.

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